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High-Performance Thermal Management

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Integrity ★ Service ★ Excellence

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Outline

- **Center for Thermal Management: Air Force Perspective**
- **What is High-Performance Thermal Management?**
- **Science Opportunities**
- **Goals and Strategy**

Air Force Research Vision

- **Enable a technological paradigm shift in thermal management through the development of;**
  - **rapidly-responding high-performance thermal management components and systems.**
  - **high-impact thermal management technologies. (e.g. power electronics, hypersonics, turbines, rocket engines, V&V for thermal M&S).**

Philosophical Approach: Center for Thermal Management

- **Academic framework, with industry input, to conduct research**
  - Fundamental physics
  - Applied sciences
  - Modeling and simulation of highly dynamical TM systems
  - Develop required mathematical and statistical tools
- **Initial research focus**
  - Modeling and simulation of dynamical TM systems
  - High-performance TM control systems and components
  - Verification and validation of dynamical TM systems
  - High-impact, high-interest thermal management technologies
- **Cultural change in approach to TM research (AKA "how to herd cats")**
  - Eliminate "silo" research approach
  - Continually evaluate applicability to high-performance system attributes and metrics
  - Rational and logical approach to TM

Current University Participation

- Purdue: lead university (Tim Fisher, Steve Heister)
- University of Illinois (Andrew Alleyne)
- Wright State University (Mitch Wolff)
- University of Dayton (John Doty)
- University of Texas (Jayathi Murthy)
- …??

Opportunity to educate and nurture next-generation scientist and engineers

Potential Industry Participation

- Boeing
- Rolls-Royce
- Lockheed
- GE
- UTC
- Honeywell
- Northrop
- Raytheon

Episodic High-Flux Heat Loads: Transient Challenges…Not Entirely New

"There had long been a standing order that guns must always move in pairs, but … the brigadier had only taken one 9-pounder with him. At first, the grape-shot from this had had a devastating effect on the Afghans…, **but soon it began to overheat, putting it out of action when it was most needed**."
–1st Anglo-Afghan War, 1840.

"…[I]t seemed as though 'the curse of God was upon those unhappy people', **for their single 9-pounder was still too hot …, and in the meantime men were falling in scores to the Afghan marksmen**."

Source: Peter Hopkirk, *The Great Game: On Secret Service in High Asia*, John Murry Publishers, London, 1990. **(emphasis added)**

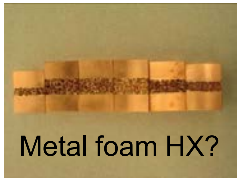
What is “High-Performance” Thermal Management?

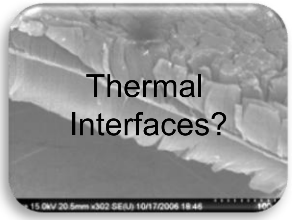
- What would a “high-performance” thermal system look like?
  - Low thermal masses?...counter to classical methodologies
  - Inherently unstable system to take advantage of rapid response?
  - Architecture differences from classical concepts?
  - New robust control methodologies and configurations?

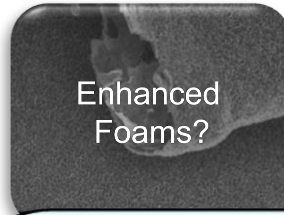
- What Attributes? Thermal system performance metrics?
  - Analogous to a Yugo vs Ferrari…energy acceleration; “not just” speed, (i.e. rate of heat rate not just heat rate)…reliability and agility in thermal management?
  - Rapid heat acquisition-transport-rejection and/or storage (O~ >10 minutes to seconds)?
  - System frequency response?
  - Component dynamical measures?
  - Efficiency?

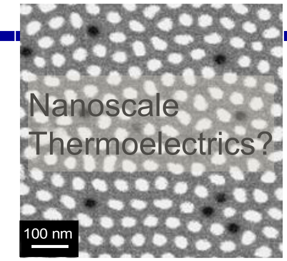
- What enabling or new science must emerge?

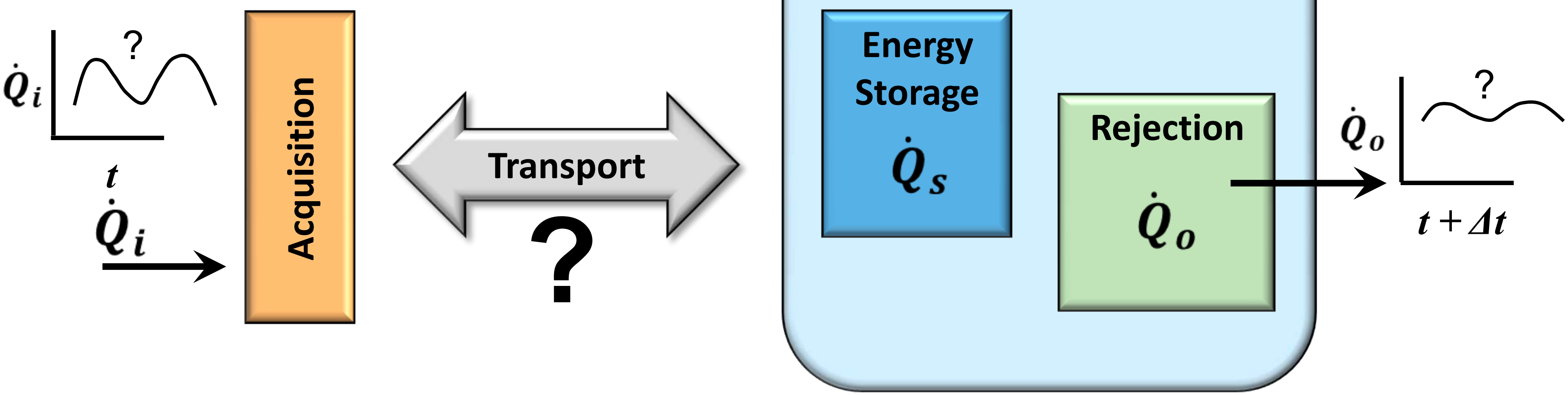
A Systems View?
What would it look like?





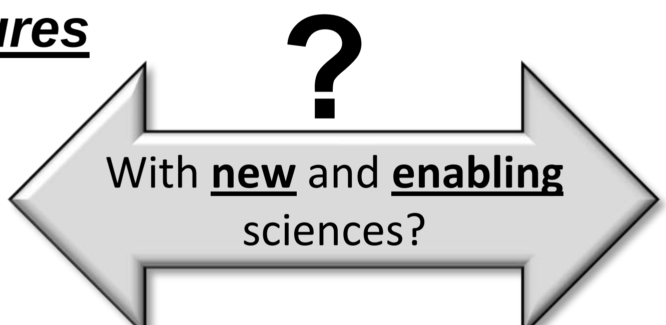






<u>Salient Features</u>

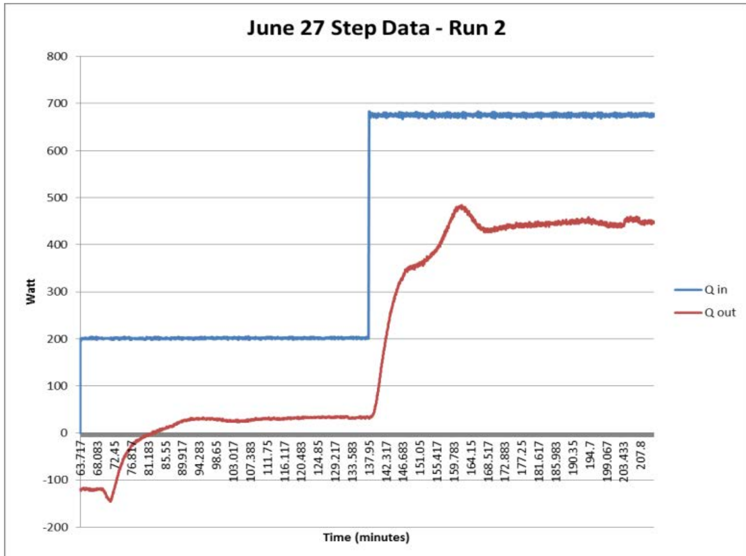
- Acquisition
- Transport
- Storage
- Rejection

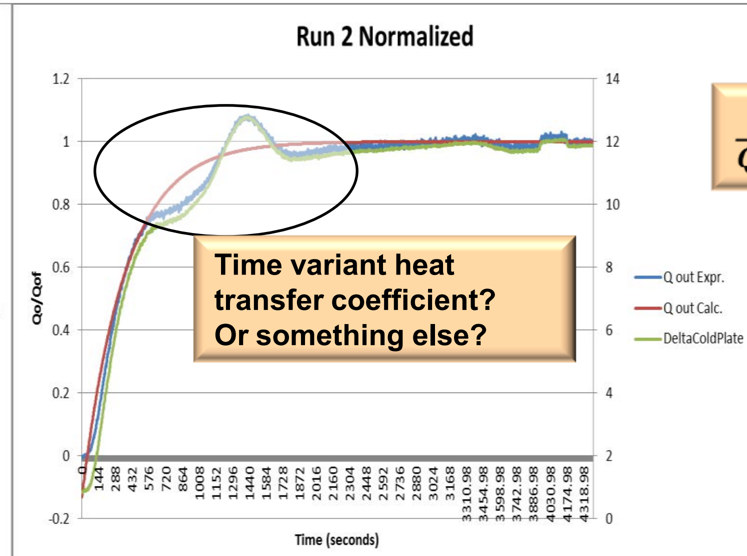


<u>Dynamic Response</u>

- What is it?
- What is needed?
- What is physically possible?

Example: LHP Step Response





$$\frac{Q_{out}}{Q_{out\ final}} = \left[1 - e^{\frac{-(t-t_{lag})}{\tau}}\right]$$

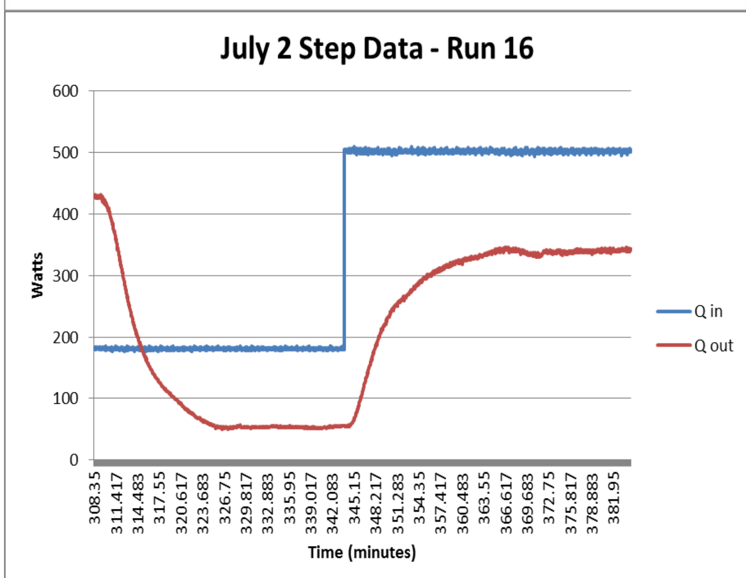
t = time

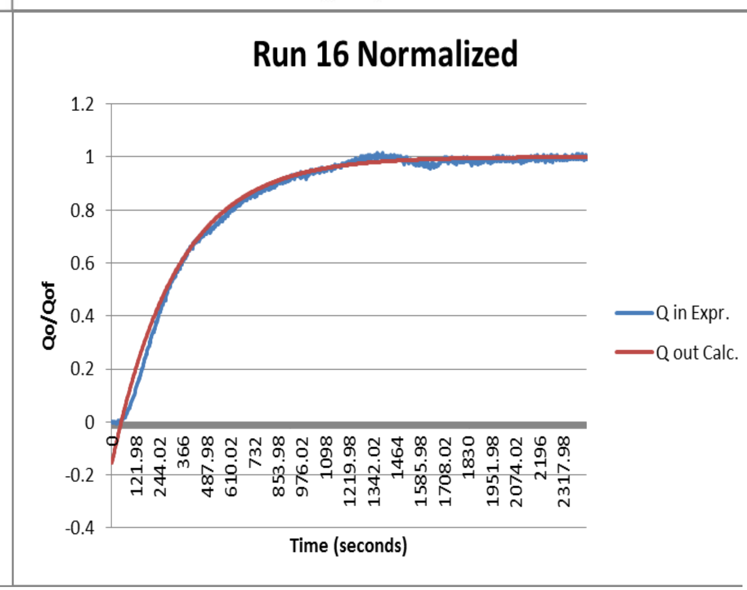
t_{lag} = time lag

τ = time constant

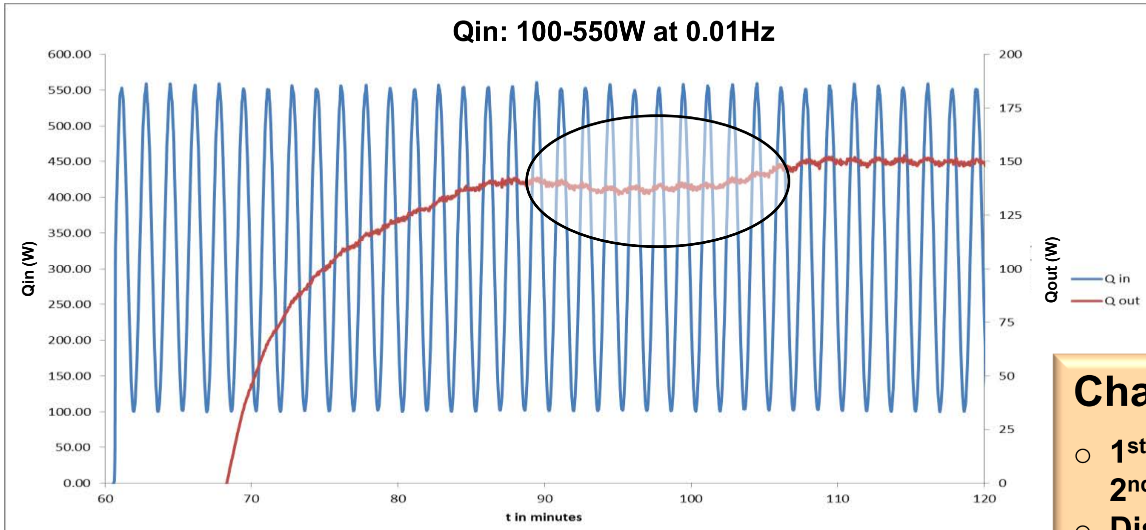
t_{lag} = 40-90s

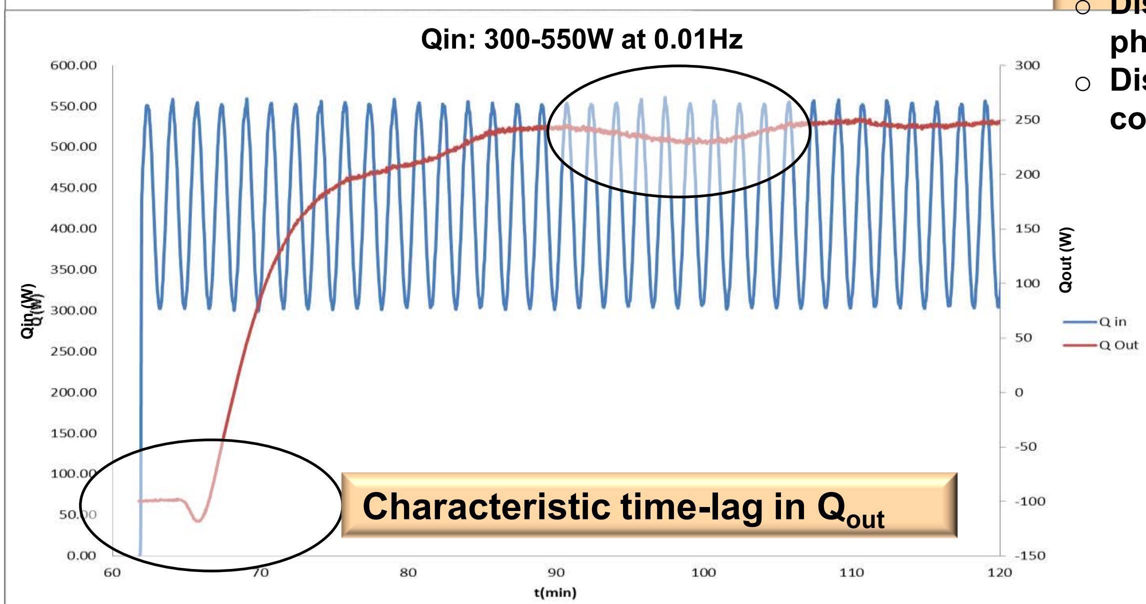
τ = 340-500s





Example: LHP Frequency Response





Characteristic Dip in Q_{out}?

- 1st order thermal mass with excited 2nd order fluid physics?
- Dissipated energy in 2-phase physics?
- Dissipated energy to open condenser? (i.e. $\delta W = PdV$?)

Efficiency Implication: Why the 'Rate of Rate' Matters

- **For a lumped system, the temperature variation with time of a 'quenched' object can be expressed as:**

$$\theta^*(t) = \frac{T - T_\infty}{T_i - T_\infty} = \exp\left[-t/\tau\right] = \exp\left[-\left(\frac{h\,A_S}{\rho\,V\,C_p}\right)t\right] = \exp\left[-Bi \cdot Fo\right]$$

  - **where T_i is the initial temperature (at t = 0) and τ is the thermal time constant (R_{th} C)**

- **The heat flow (the 'rate') through the boundary is**

$$Q(t) = hA_S\left(T - T_\infty\right) = \theta^*(t)\,hA_S\left(T_i - T_\infty\right)$$

$$= \exp\left[-t/\tau\right]\frac{C}{\tau}\left(T - T_\infty\right)$$

Why the Rate of Rate Matters, cont'd

- **The rate of change of Q(t) is**

$$Q'(t) = \frac{dQ(t)}{dt} = \exp\left[-t/\tau\right]\frac{-C}{\tau^2}\left(T_i - T_\infty\right) = \frac{-Q(t)}{\tau}$$

- **The system entropy generation rate is**

$$\dot{S}_{gen}(t) = \frac{Q(t)}{T_\infty} - \frac{Q(t)}{T(t)} = Q(t)\left[\frac{1}{T_\infty} - \frac{1}{q^*(t)\Delta T_i + T_\infty}\right]$$

$$\approx \frac{Q(t)}{T_\infty}\left(\frac{q^*(t)\Delta T_i}{T_\infty}\right) = \frac{Q(t)}{T_\infty^2}\frac{\boxed{\tau}}{C}Q(t) = \frac{-1}{\boxed{Q'(t)}}\frac{Q^3(t)}{CT_\infty^2}$$

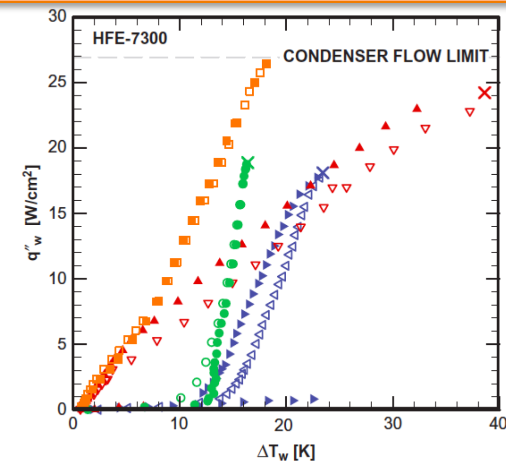
- Higher 'rate of rate' (*Q'*) (lower τ) decreases entropy production, making **<u>more efficient systems</u>** (as optimized with 2nd Law analysis)
- Addition of thermal mass (higher τ) slows system; less efficient but adds safety buffer

Paradigm Shift in the Technical Approach to Thermal Management

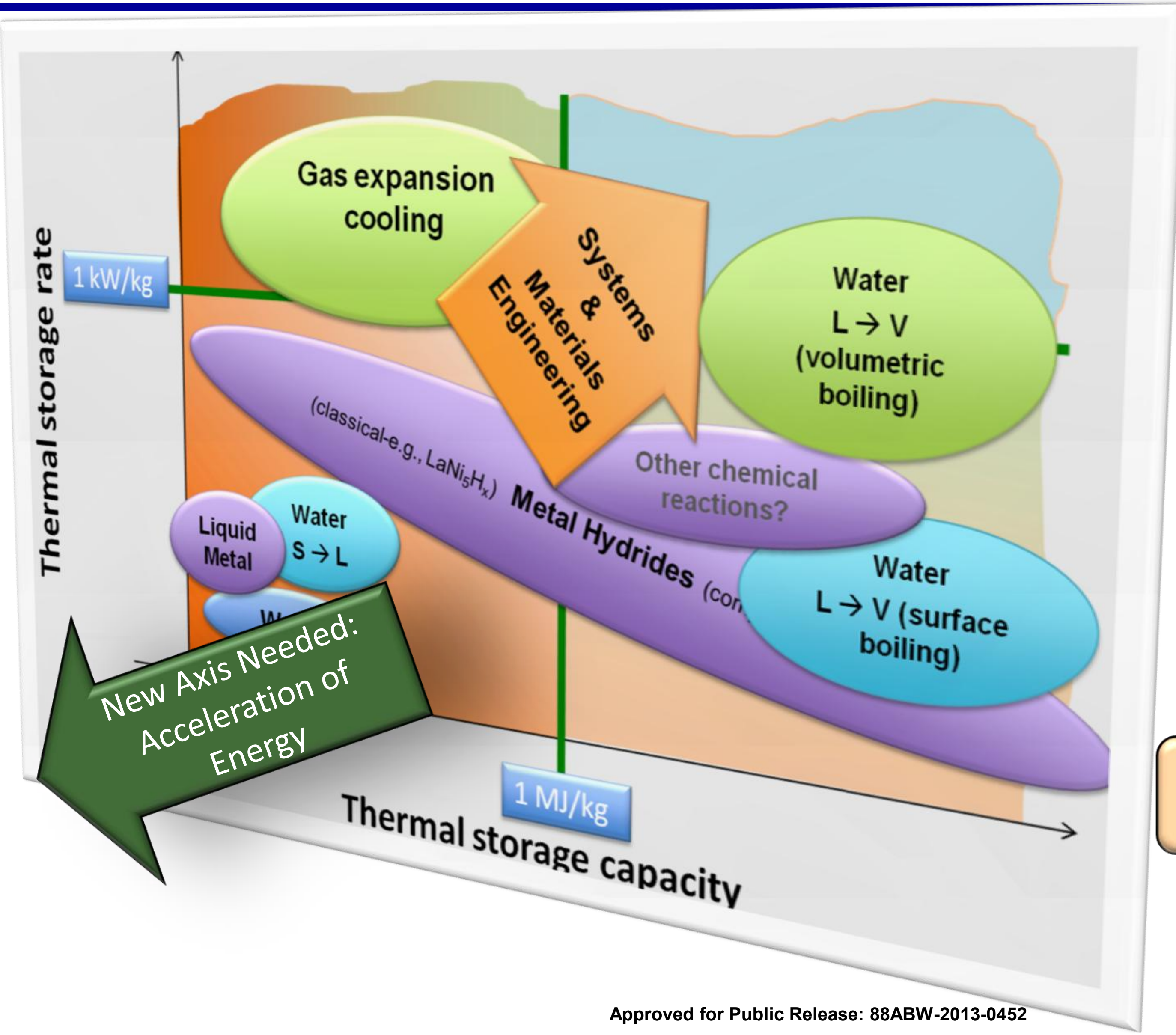
- **Past/current 'thermal management' paradigm**
  - Focus on steady-state performance
  - Design for worst-case heat flux
  - 'Wait' for the heat to arrive; i.e. increased temperature
    - thermal solution: to 'engage' and persist ***indefinitely*** by design
    - Temperature control without considering rate of heat transport in a dynamic sense
  - Rate of energy as a performance metric

- **Emerging heat loads are not amenable to this paradigm**
  - Acceleration of energy as a performance metric
  - Transient thermal system metrics needed
  - Disparate characteristic time-scales
  - Ultra-high and dynamic heat loads require anticipatory measures/control
  - Loads are highly episodic—no steady-state exists
  - Failures occur during highly dynamic loads

Boiling curve (McHale et al., Nano. Micro. Thermophys. Eng., 15 133, 2011).



Typical Steady-State Thermal Storage Design Space



New Attributes Needed:

- **Temporal scale ("acceleration" of energy as a performance metric)**
- **Coupling of dynamic thermal loads**
- **System Integrability**

Implication for Science Opportunities?

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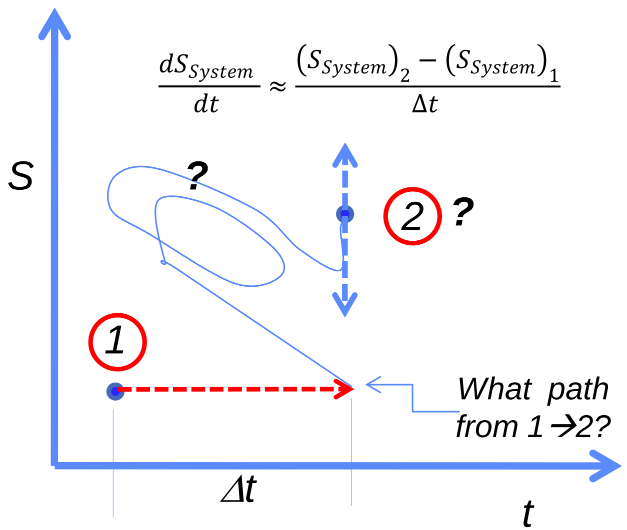
2nd Law Path Implication: Account for Dynamic Entropy Generation

- **Typical path-*independent* Approximation**

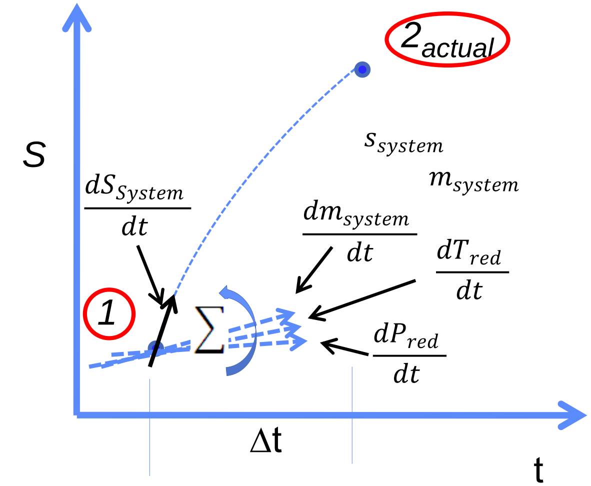
$$\dot{S}_{Gen} = \left\{ \frac{(S_{system})_2 - (S_{system})_1}{\Delta t} \right\} - \left[\{\dot{S}_{In}\}_{Heat,Mass} - \{\dot{S}_{Out}\}_{Heat,Mass} \right]$$



Quasi-steady or steady-state approach does not specify how system moves from state 1 to 2

★ **Proposed path-related Approximation****

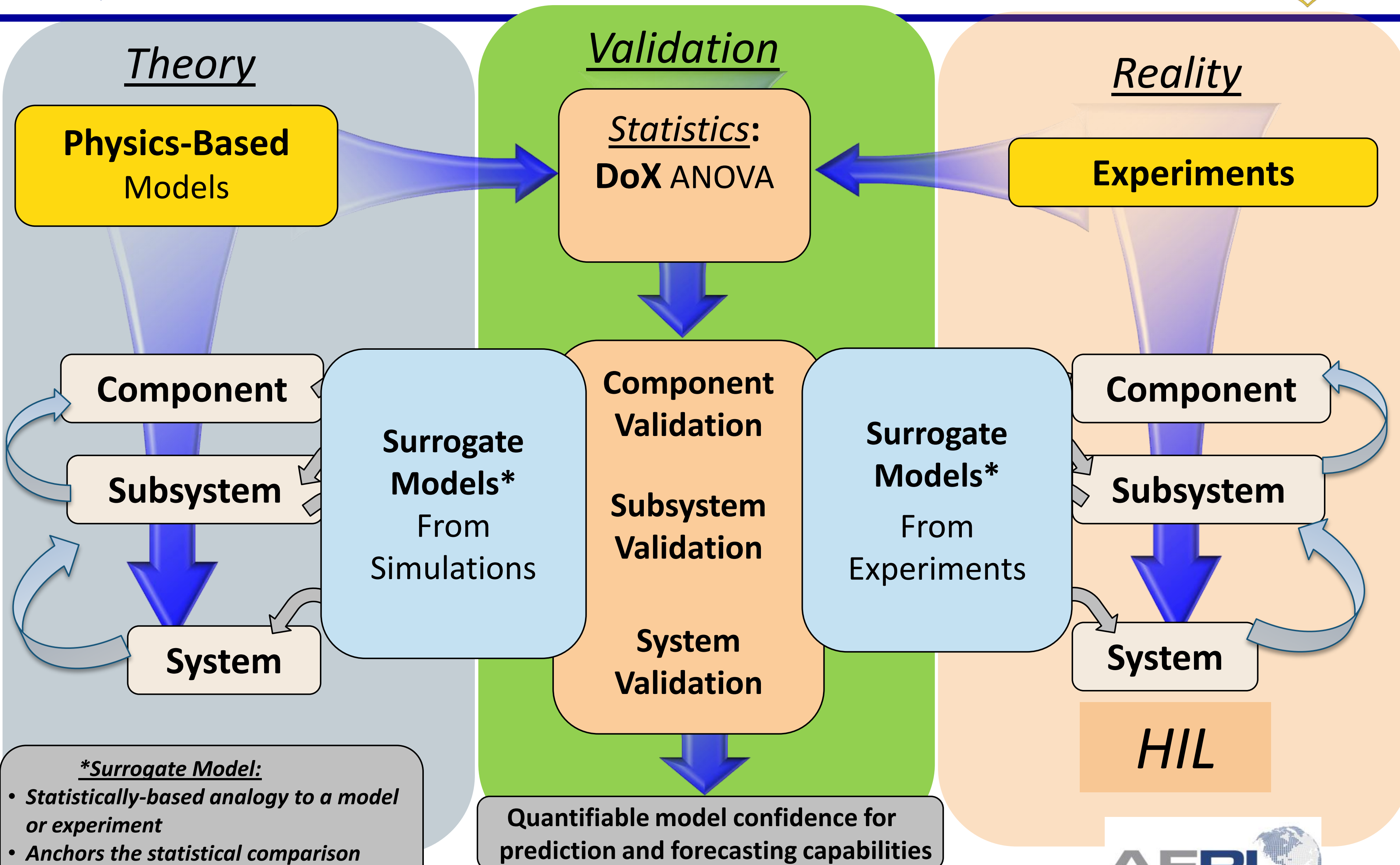
$$\dot{S}_{Gen} = \left\{ s_{system} \frac{dm_{system}}{dt} + m_{system} \left\{ \left(\frac{\partial s_{system}}{\partial T}\right) \frac{dT_{red}}{dt} + \left(\frac{\partial s_{system}}{\partial P}\right) \frac{dP_{red}}{dt} \right\} \right\} - \left[\{\dot{S}_{In}\}_{Heat,Mass} - \{\dot{S}_{Out}\}_{Heat,Mass} \right].$$



Proposed approach indicates how system likely moves from state 1 to 2

**Doty, et.al.

V&V Implication:
New Mathematical and Statistical Approaches



Potential Science Opportunities

- Fundamental physics encompassing highly dynamical phenomena
  - Non-equilibruim physics of thermodynamics and heat transfer
  - Exploitation of metastable regions far from equilibrium (e.g. metastable two-phase regions)
  - Theoretical and experimental thermodynamics
  - Quantum-atomistic-molecular physics for heat transfer

- Modeling and simulation of highly dynamical thermal management systems
  - Coupled time-accurate dynamic 1st and 2nd Law analysis beyond classical approaches
  - Stability analysis of complex coupled systems

- Advanced non-linear control theory for stable and unstable thermal management systems

- Rational and logical approach to the “science of integration” for complex systems

- Development of mathematics supporting V&V of non-linear dynamical systems

Summary

- **Paradigm shift in the technical approach to thermal management**
- **Will require defining and developing:**
  - **New foundational science concepts**
  - **Robust time-accurate and physics-based modeling**
  - **Rigorous statistically-based V&V**
  - **Well-posed experimentation**